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14. ABSTRACT
On the numerical model development front, we are tackling both ends of the fluid modeling spectrum simultaneously. The low-fidelity simulation capability for the formation process in RMF FRC thrusters (based on the Hugrass model) and a high-fidelity multifluid capability for both theta-pinch and RMF FRCs provides us with both an extremely rapid engineering-level code to quickly simulate behavior from the FRC experiments at AFRL/RQRS and a detailed simulation tool to serve as a workhorse for our scientific investigations. These codes presently exist in a standalone form but are all designed for smooth integration into our framework code at AFRL/RQRS.

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Annual Report 2015
High Fidelity Modeling of Field-Reversed Configuration (FRC) Thrusters
Report Start Date: 10/01/2014

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Justin Koo, AFRL/RQRS

On the numerical model development front, we are tackling both ends of the fluid modeling spectrum simultaneously. The low-fidelity simulation capability for the formation process in RMF FRC thrusters (based on the Hugrass model) and a high-fidelity multifluid capability for both theta-pinch and RMF FRCs provides us with both an extremely rapid engineering-level code to quickly simulate behavior from the FRC experiments at AFRL/RQRS and a detailed simulation tool to serve as a workhorse for our scientific investigations. These codes presently exist in a standalone form but are all designed for smooth integration into our framework code at AFRL/RQRS.

Initial application of these codes is to both RMF and theta-pinch FRC simulations. The results thus far are limited to two-dimensional (either radial-axial or radial-azimuthal) and do not reflect the full integration of our circuit models. These assumptions purposely avoid some of the system complexity; however, our development plan addresses these issues and we will be revisiting these simulations as our computational capabilities mature. Moreover, since the multifluid capability is based on an unstructured discontinuous Galerkin formulation, extension from 2D to 3D is fairly straightforward.

Among our most promising simulations to date are simulations of the cross section of an RMF FRC thruster during the plasmoid formation phase of operation. This phase of operation of the FRC is in a very low resistivity regime, previously studied with a single fluid Hall-MHD code by Milroy[1]. With our multifluid code, we have been able to explore this collisionless limit by setting the collisional exchange terms to zero. Simulations of RMF formation for a singly-charged hydrogen plasma are shown in Figure 1. At the much longer time of $t = 4\ \mu s$ from the start of formation, this process can be seen to culminate in a much more robust closed field topology in Figure 2. At this advanced time, the mass density plots for the electron and the ions show that confinement of the plasma has started, which could eventually lead to a stable FRC; however, the simulations become unstable as time evolves leading to the magnetic island collision with the boundary and destruction of the close magnetic field structure. The causes of this disruption are not well understood at this moment and additional investigation is need; nevertheless, this formation sequence compares well with the results of the Hall-MHD code.

[1] R. D. Milroy, "A magnetohydrodynamic model of rotating magnetic field current drive in a field-reversed configuration," *Physics of Plasmas,* vol. 7, no. 10.

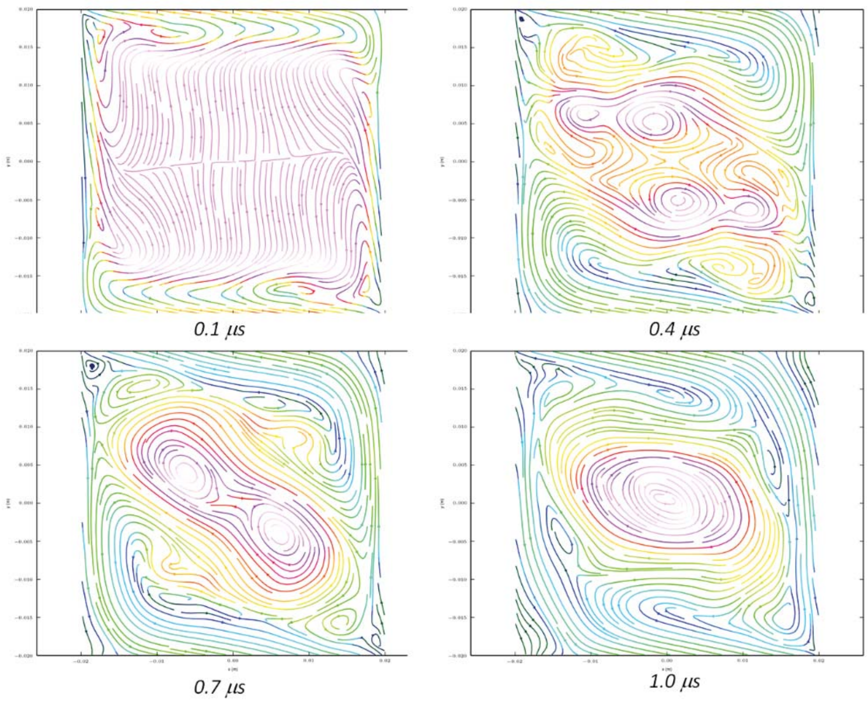

Figure 1. Magnetic field evolution using a RMF. Reconnection of the field lines lead to the formation of a single magnetic island

While successful in verifying similar 2D magnetic reconnection in the collisionless limit of multi-fluid simulation, these initial simulation represent only the beginning of our investigation into FRC formation physics. Another active area of investigation is the addition of neutrals to the multifluid models - the interaction of all three fluids greatly increases the complexity of the problem considerably. Ionization, recombination and excitation become relevant and need to be added to the simulations, as well as collisional physics between each pair (e.g. ion-electron, ion-neutral, neutral-electron).

In addition, it is well understood throughout the plasma modeling community that 3D magnetic reconnection is fundamentally different from the 2D reconnection process observed in these simulation. As we begin to compare with experiments, impurities such as heavy ions stripped from the chamber walls can increase the plasma radiation considerably and can lead to cooling of the plasma. Although fully coupled treatment of radiation transport is beyond the scope of this project, development of ancillary physics models for realistic FRC simulation, including Collisional-Radiative models for Argon and other atomic gases of interest and detailed Coil/Circuit models to evaluate coupling of the external electrical circuit to the plasma, have already been performed and the resulting libraries will be integrated into the framework code in the next year of this effort.

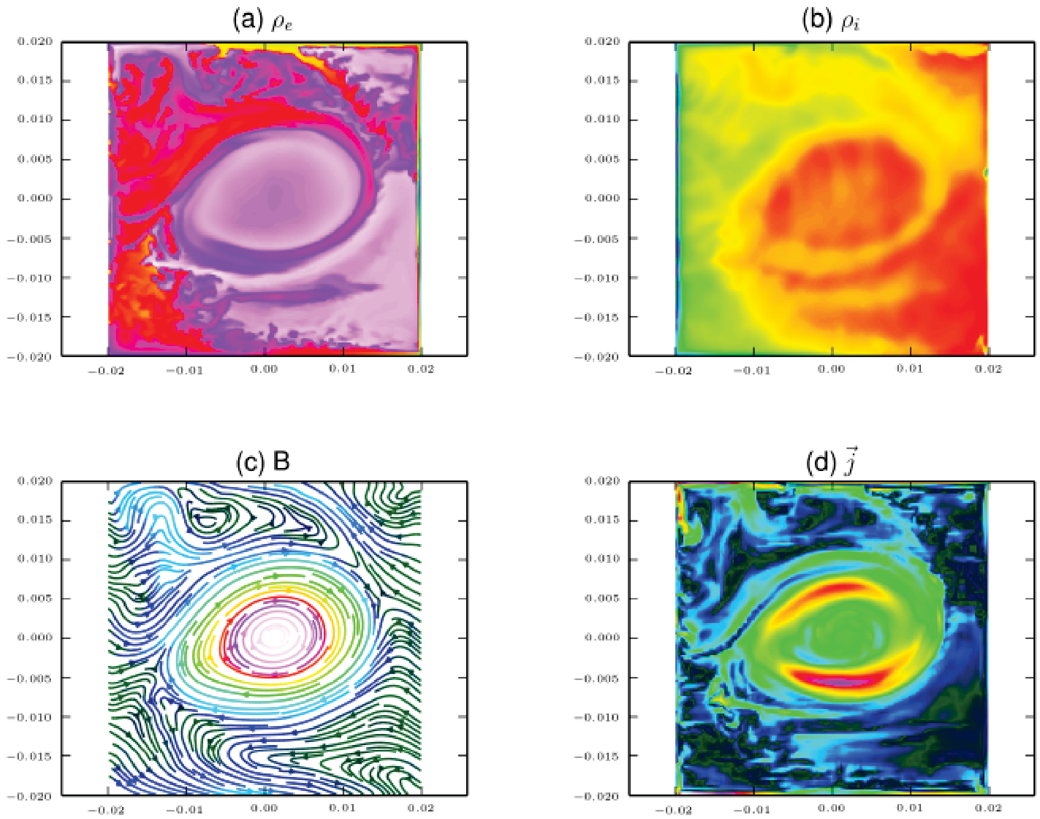

Figure 2. Electron mass density (a), ion mass density (b), magnetic field (c), and current (d) profiles for a collisionless multifluid plasma simulation using RMF boundary conditions.

Attachments (These documents were presented outside of the reporting timeframe but represent work accomplished during the reporting period.)

- Review slides from Fall 2015 AFOSR Review (1 Oct 2015, Arligton, VA)
- Poster from APS Division of Plasma Physics (16-20 Nov 2015, Savannah, GA)